US ARMY RDECOM

U.S. Army Research, Development and Engineering Command

Monolithically Integrated Micro Flapping Vehicles

ARL

TECHNOLOGY DRIVEN. WARFIGHTER FOCUSED.

Jeffrey S. Pulskamp, Ronald G. Polcawich, Gabriel L. Smith, Christopher M. Kroninger

Report Documentation Page

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14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**25**	

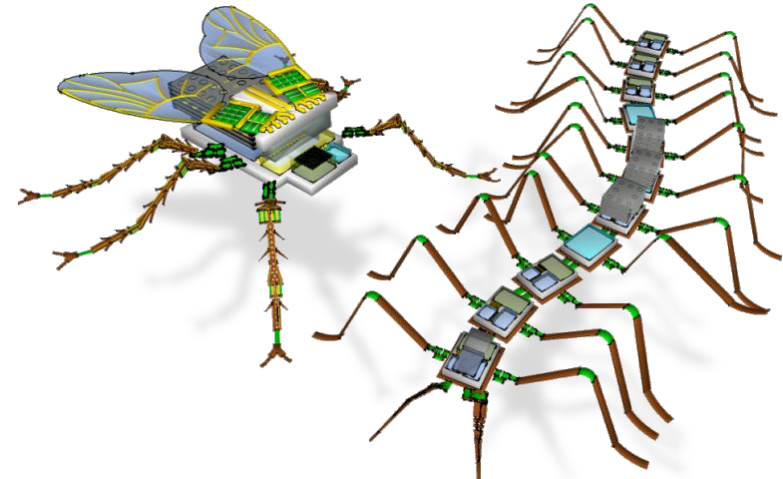# Millimeter-scale Robotics Technology

Objective

- **Develop and demonstrate technologies to provide the Army a low-cost, low observable, mobile sensor platform**

Benefits

- **Extreme scale, MEMS enabled platforms can provide unprecedented low-observability & accessibility & integrated multifunctionality at low unit cost**

Conceptual illustrations of highly integrated mm-scale low-cost, low observable, mobile sensor platforms for empowering and unburdening the soldier

Technical Barriers

- Biological **mobility** with nontrivial **load bearing**

- Scale-limited **power & energy**

- Simplest systems still require **high degree of integration**
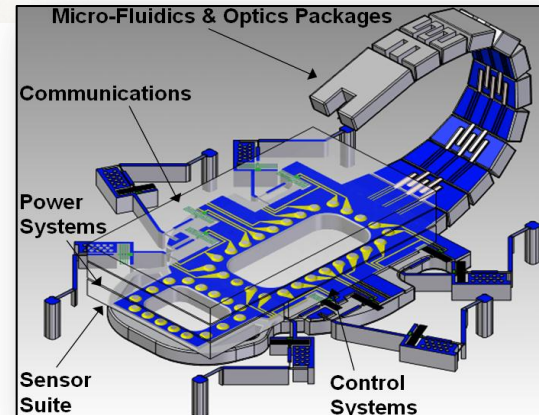
- Design **complexity**

Approach

- Develop high performance **PZT MEMS actuation** and biological-like mechanisms

- **Leverage** thin film batteries and **collaboratively develop** integrated power solutions

- Exploit **MEMS, microelectronics**, and the limited application of standard **packaging**

- **Holistic design** of system, component, device levels

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ARL Millimeter-scale Robotics Research

Collaborations with UCSB, IMT, ARL –SEDD, ARL-VTD, ARL-WMRD, UMich, & Penn St.

Objective: Provide the Army a low-cost, low observable, mobile sensor platform

Subsystems with PiezoMEMS integration potential:

- Mobility:

- Sensing:
  - Proprioceptive
  - Payload

- Communications:
  - RF MEMS

- Power:
  - Transformers
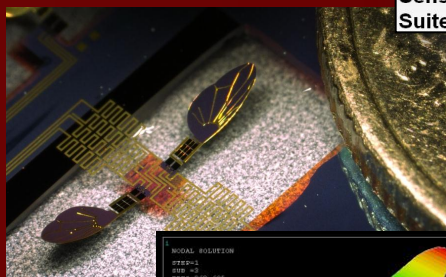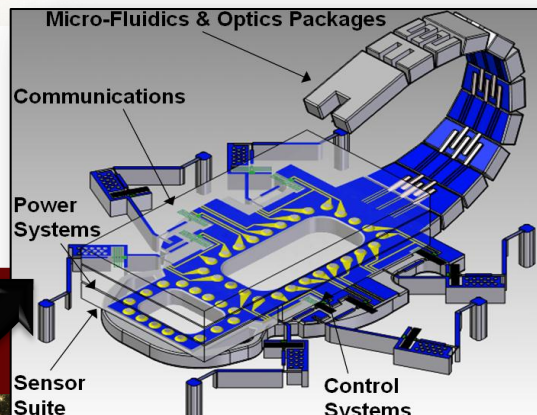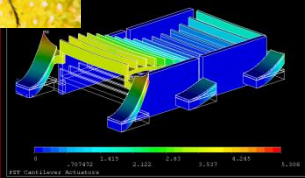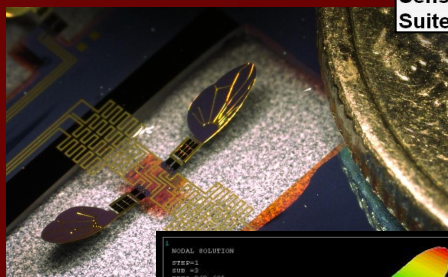 - Harvesting

- Control:
  - Mechanical Logic
  - Memory

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ARL Millimeter-scale Robotics Research

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Objective: Provide the Army a low-cost, low observable, mobile sensor platform

Micro-Fluidics & Optics Packages

Communications

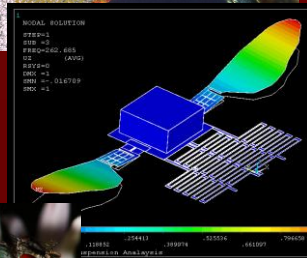Power Systems

Sensor Suite

Control Systems

Subsystems with PiezoMEMS integration potential:

- Mobility:
- Sensing:
  - Proprioceptive
  - Payload
- Communications:
  - RF MEMS
- Power:
  - Transformers
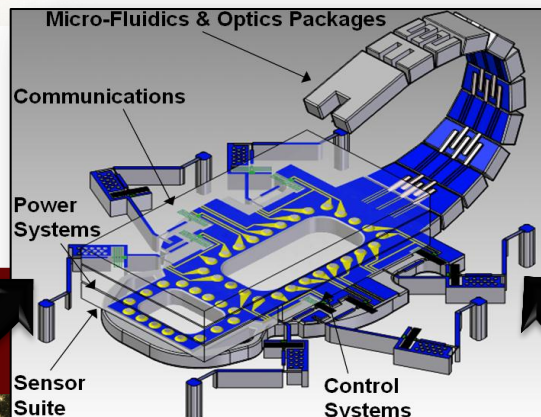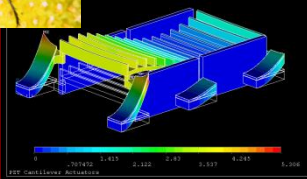 - Harvesting
- Control:
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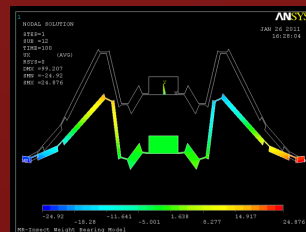**Mm-Scale Flight**
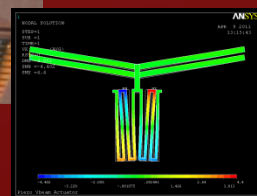

Flapping Flight

MEMS Pumpjet

ARL Millimeter-scale Robotics Research

Collaborations with UCSB, IMT, ARL –SEDD, ARL-VTD, ARL-WMRD, UMich, & Penn St.

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Objective: Provide the Army a low-cost, low observable, mobile sensor platform

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- Communications:
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Micro-Fluidics & Optics Packages

Communications

Power Systems

Sensor Suite

Control Systems

Mm-Scale Flight
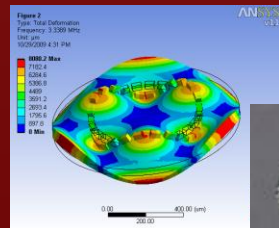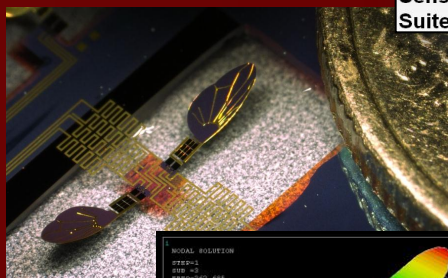
Flapping Flight

MEMS Pumpjet

Mm-Scale Ground Mobility

Platform Design

Actuation & Mechanisms

Ultrasonic Motors

Reversible Adhesion

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ARL Millimeter-scale Robotics Research
Collaborations with UCSB, IMT, ARL –SEDD, ARL-VTD, ARL-WMRD, UMich, & Penn St.

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Objective: Provide the Army a low-cost, low observable, mobile sensor platform
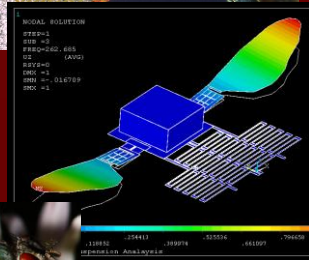
Subsystems with PiezoMEMS integration potential:

- Mobility:

- Sensing:
  - Proprioceptive
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- Communications:
  - RF MEMS

- Power:
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  - Harvesting
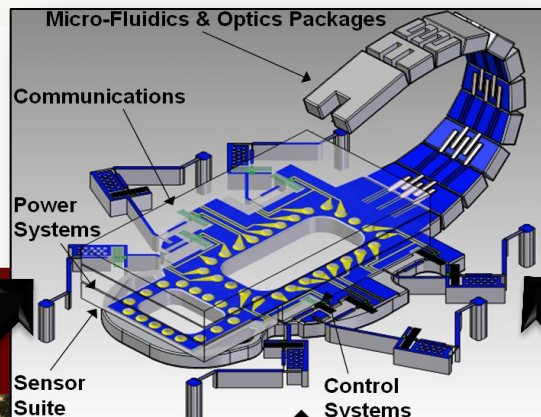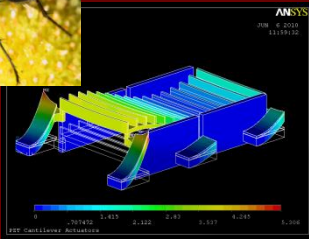
- Control:
  - Mechanical Logic
  - Memory

Micro-Fluidics & Optics Packages
Communications
Power Systems
Sensor Suite
Control Systems

Mm-Scale Flight

Flapping Flight

MEMS Pumpjet

Mm-Scale Ground Mobility

Platform Design

Actuation & Mechanisms

Ultrasonic Motors

Reversible Adhesion

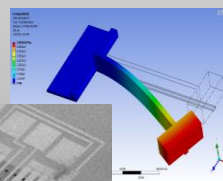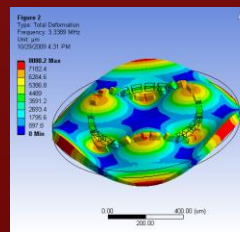## Proprioceptive Sensing

PiezoMEMS Haltere
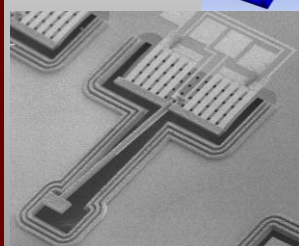
Leveraged Research

MEMS logic
Integrated Power
RF MEMS

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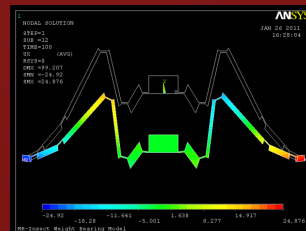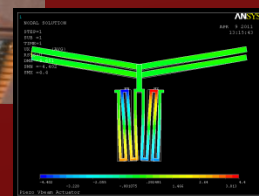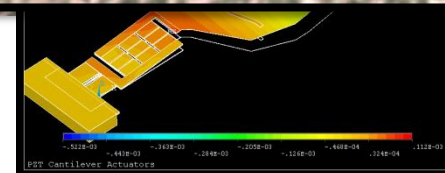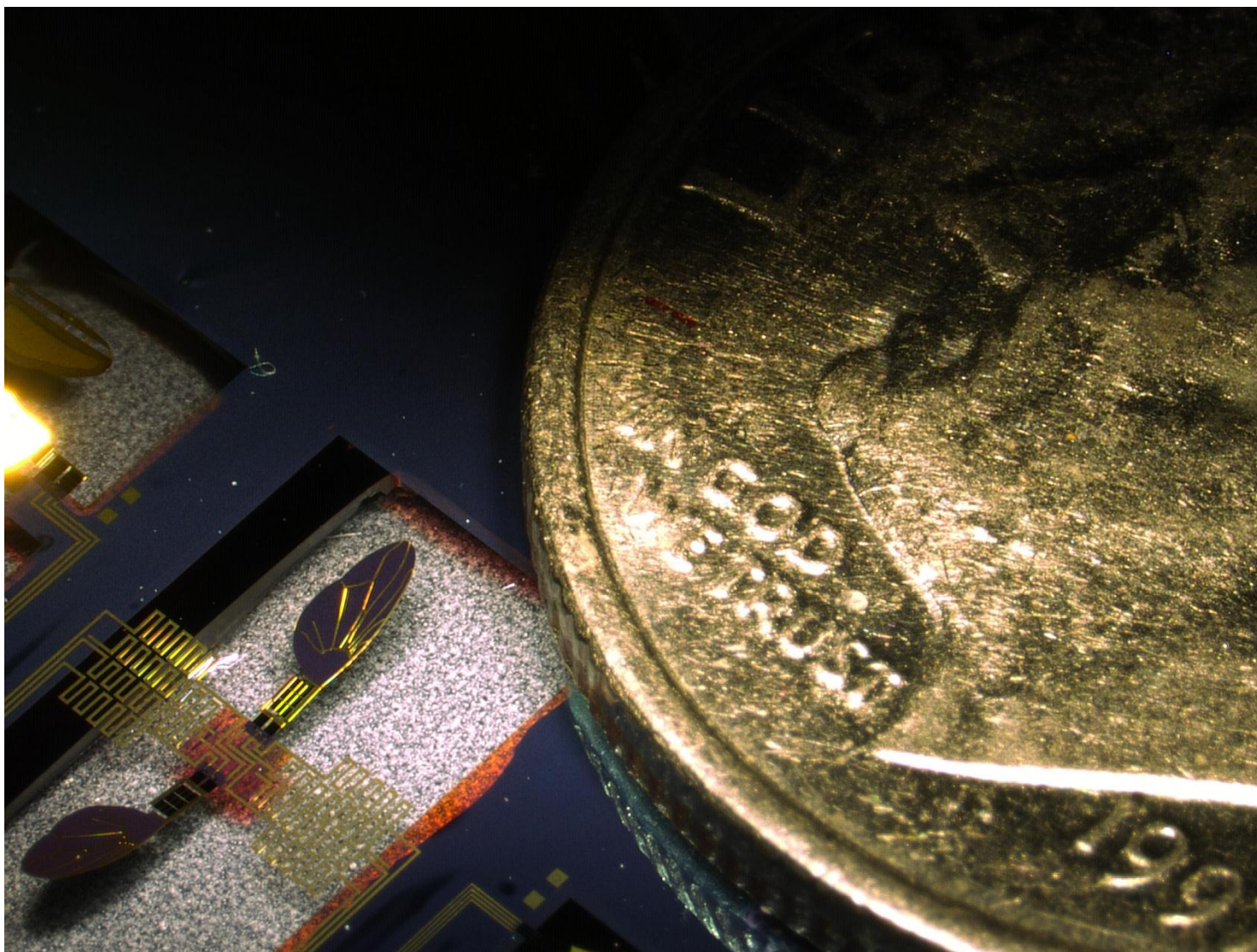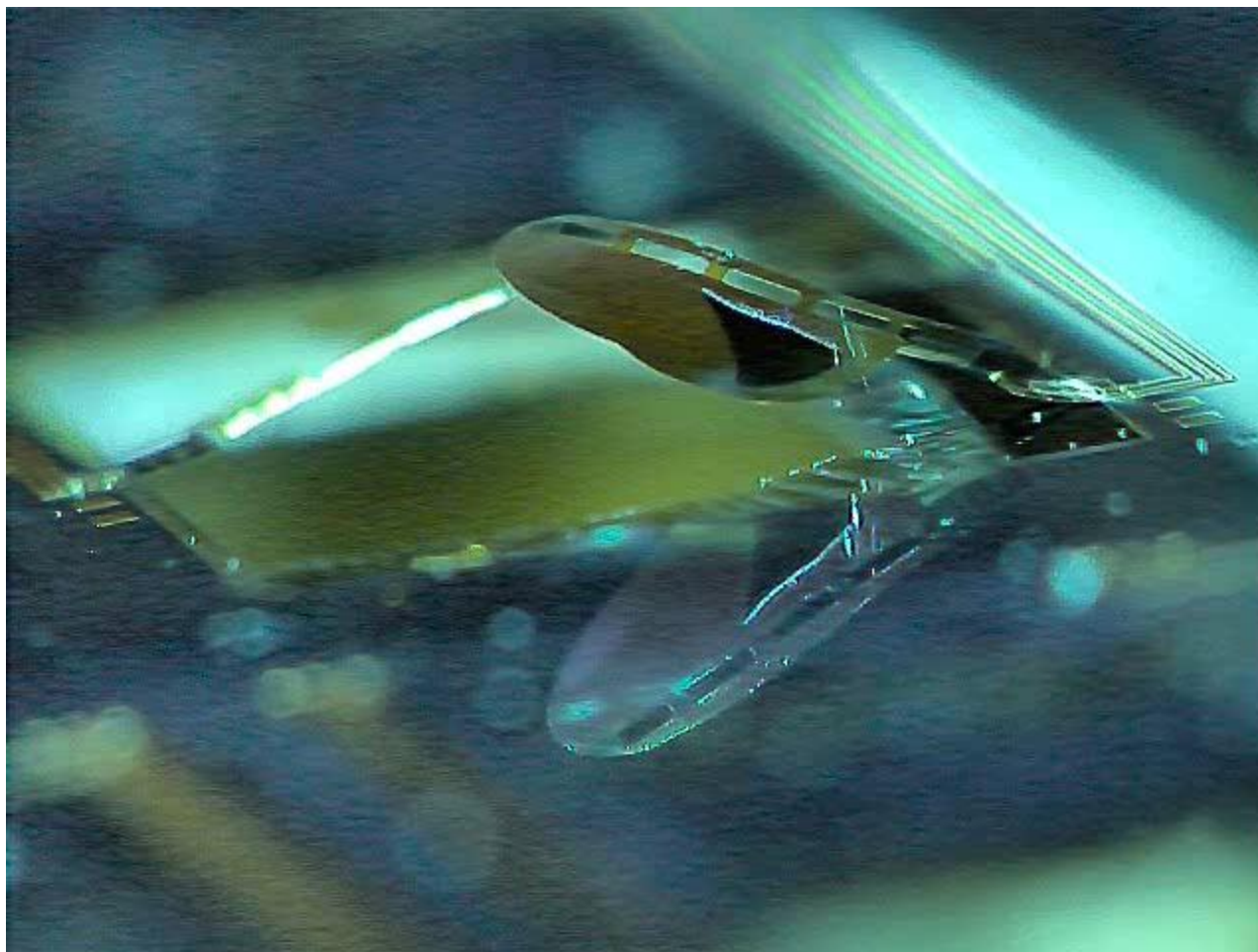
- Internal ARL multi-directorate research

- Goals:

  - Initial (DRI): Feasibility assessment & demonstration

    - Produce lift and flight characteristics similar to th... in the same size class

  - Current (Mission): Develop enabling tech...

- Design:

  - 2 dof actuation

  - Thin film wings reinforced with stiff vena...

- Accomplishments:

  - ~120⁰ stroke amplitudes at 10V drive (re...

  - ~45⁰ pitch amplitudes at 25V drive (quas...

  - frequencies similar to fruit fly (150-250Hz)

Stroke Actuat...
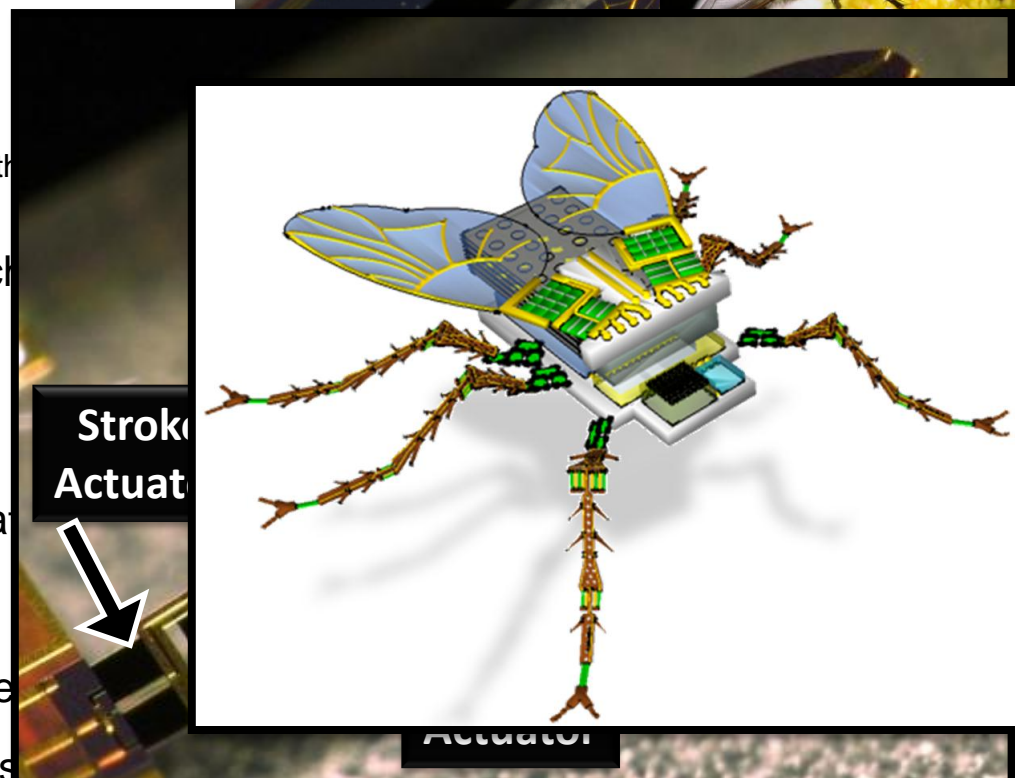
Actuator

Two degree of freedom actuation

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Key System-level Questions:

– Power

– Load Bearing

– Framing the Mobility Design Problem
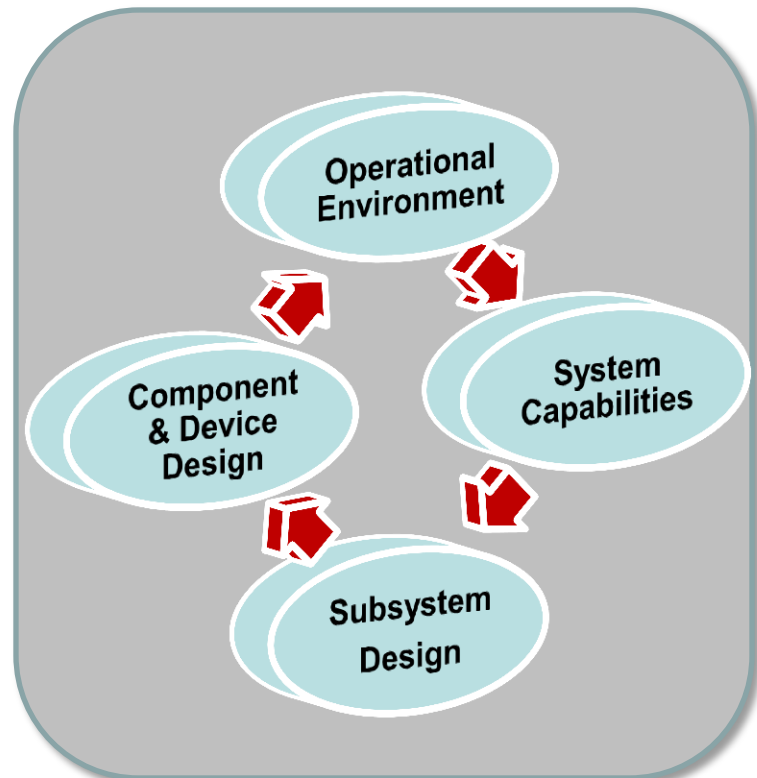
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Key System-level Questions:
- Power
- Load Bearing
- **Framing the Mobility Design Problem**

Thin Film Battery Performance

Power vs Size | Mass vs Size

Mass per leg | Power vs Mass | Flight Mass

Energy

Power vs Limb Properties | Other models | Power vs Wing Properties

Speed, Endurance, etc.

Design

Operational Environment

Component & Device Design | System Capabilities

Subsystem Design
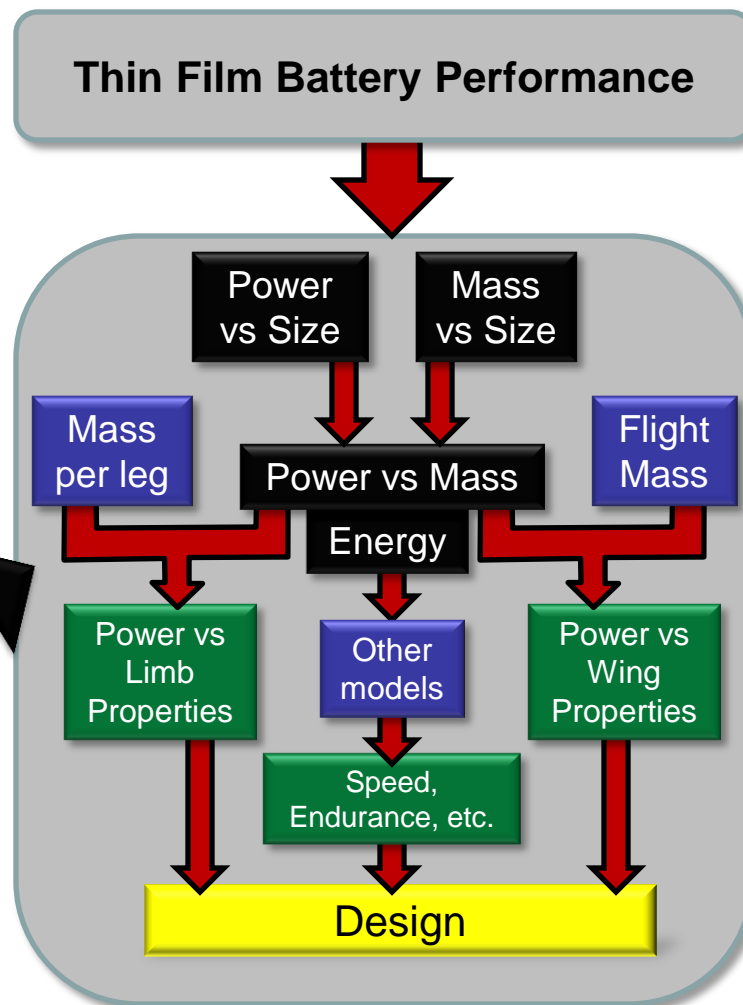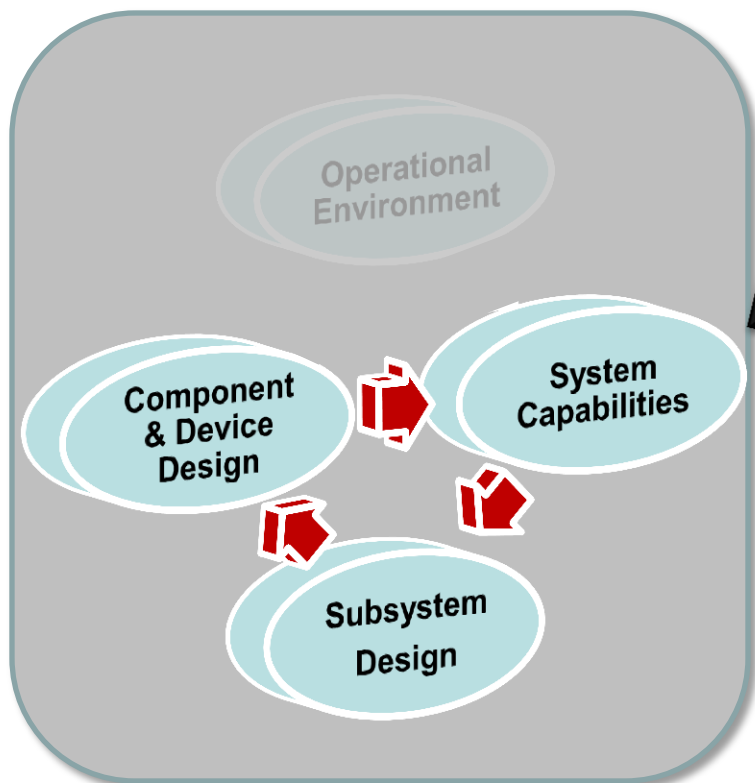
Key System-level Questions:

- **Power**
- Load Bearing
- Framing the Mobility Design Problem

Power Numbers based on demonstrated Thin Film Battery Technology

~10 to 1000 mW available at millimeter-scale

Key System-level Questions:

- **Power**
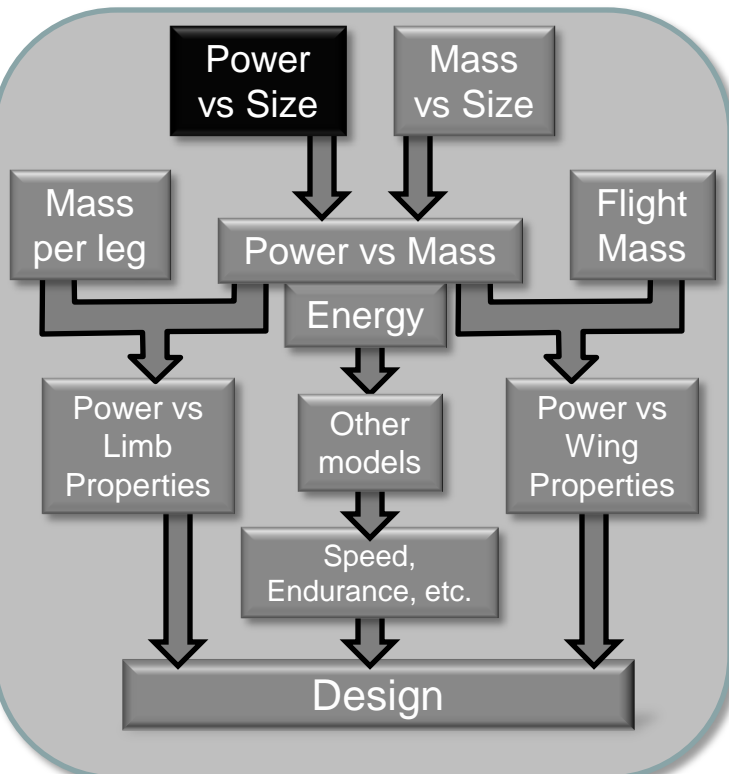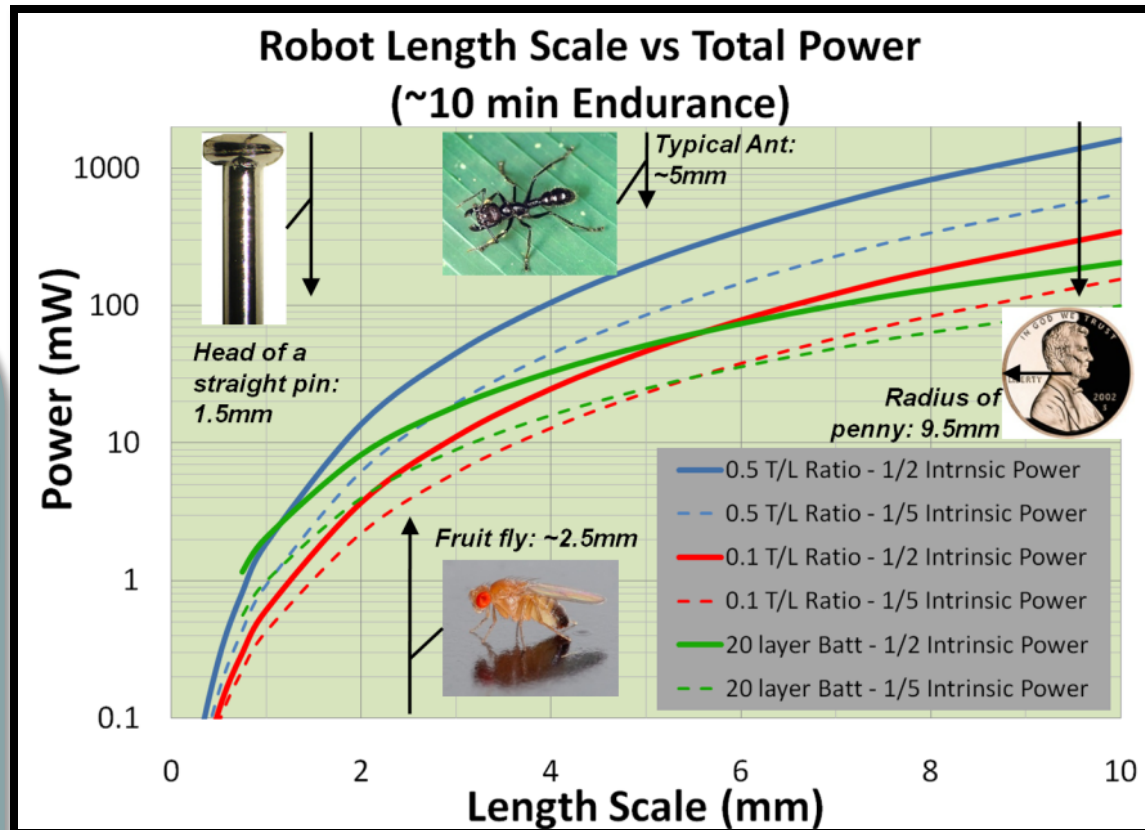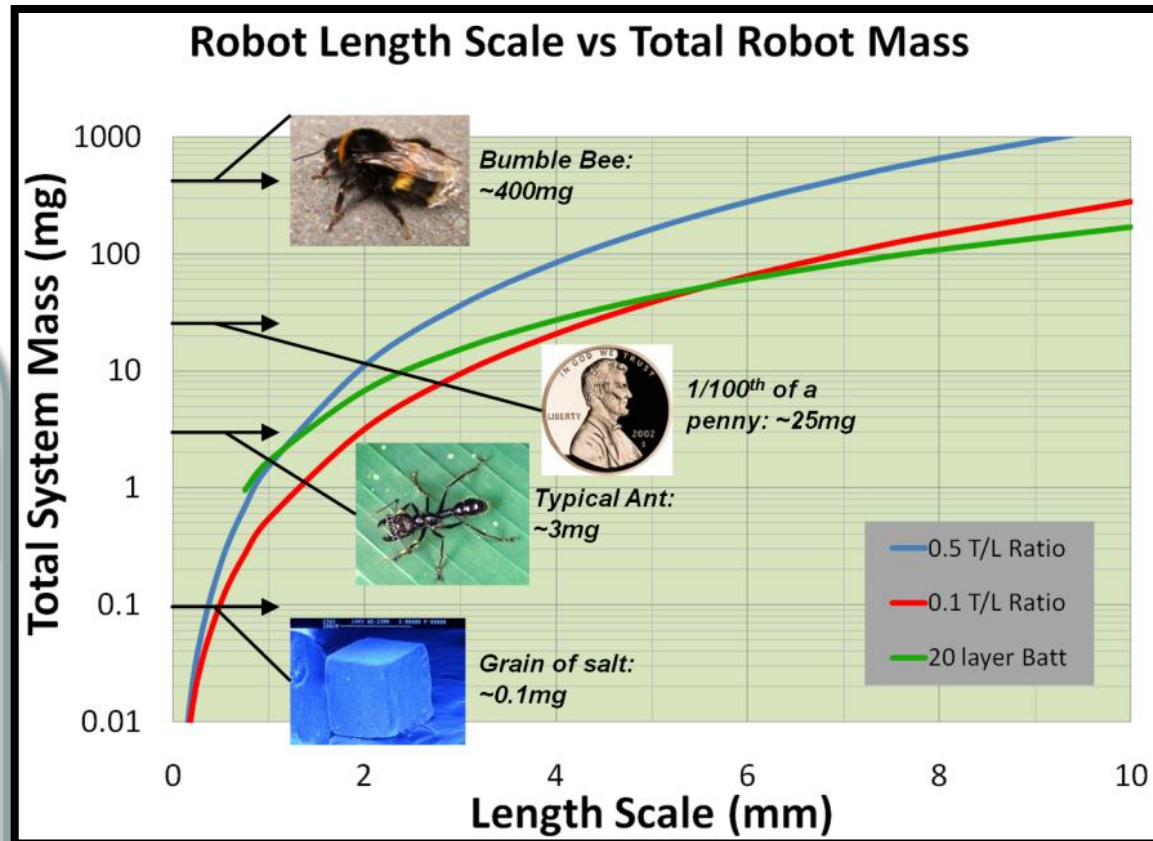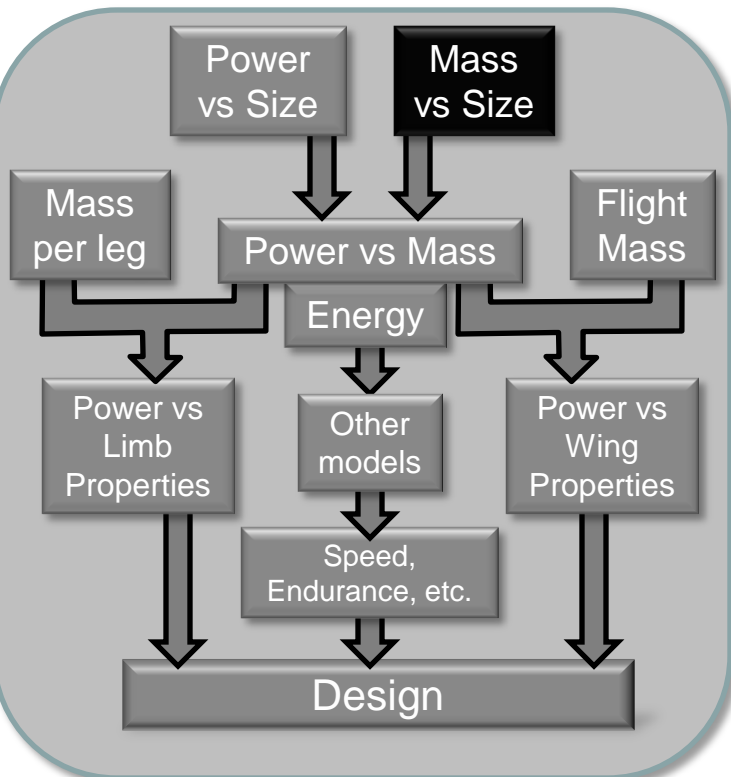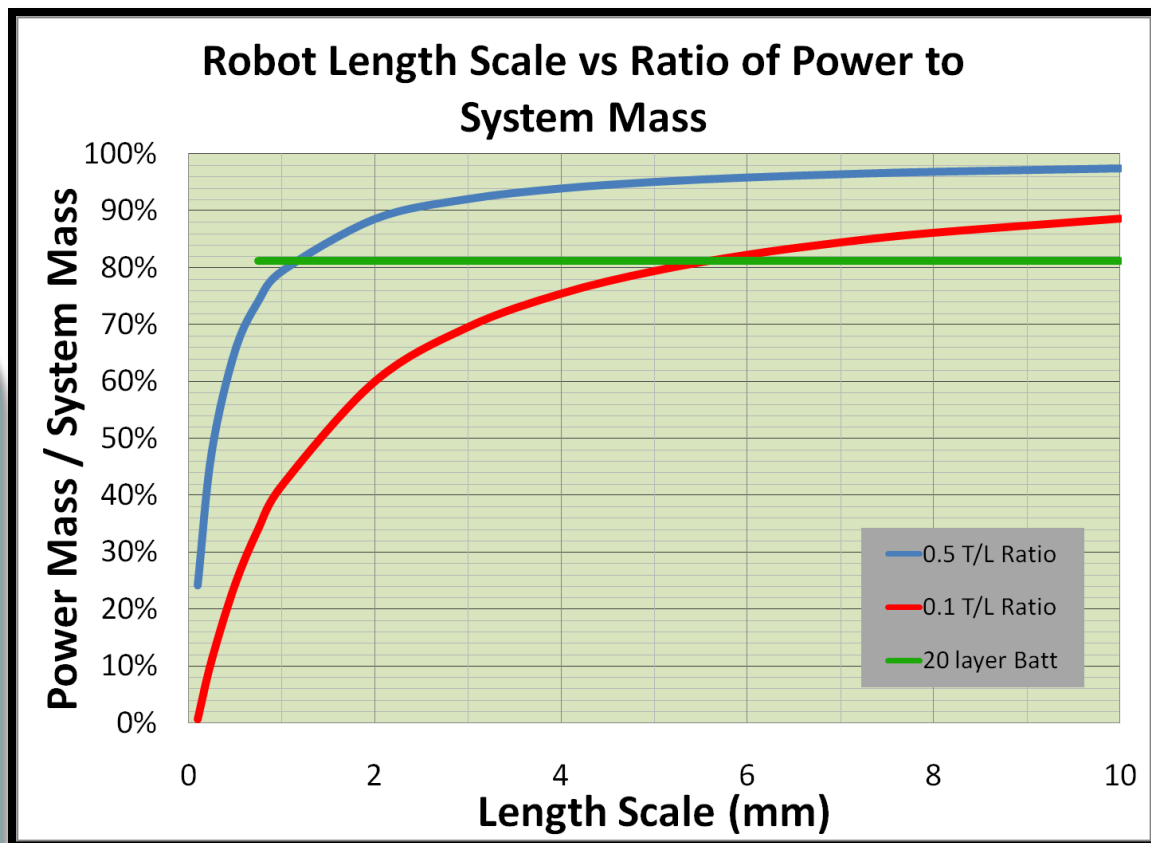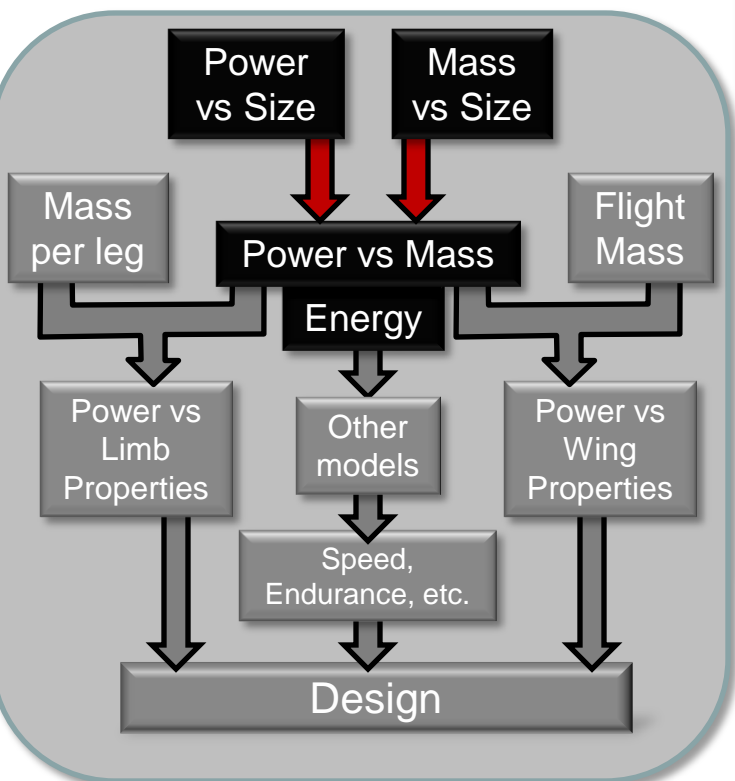
- Load Bearing

- Framing the Mobility Design Problem

~10 to 1000 mg likely at millimeter-scale

Key System-level Questions:

– **Power**

– Load Bearing

– Framing the Mobility Design Problem

Power vs Size	Mass vs Size

Mass per leg	Power vs Mass	Flight Mass

Energy

Power vs Limb Properties	Other models	Power vs Wing Properties

Speed, Endurance, etc.

Design

Robot Length Scale vs Ratio of Power to System Mass

Legend:
- 0.5 T/L Ratio
- 0.1 T/L Ratio
- 20 layer Batt

Y-axis: Power Mass / System Mass (0% to 100%)
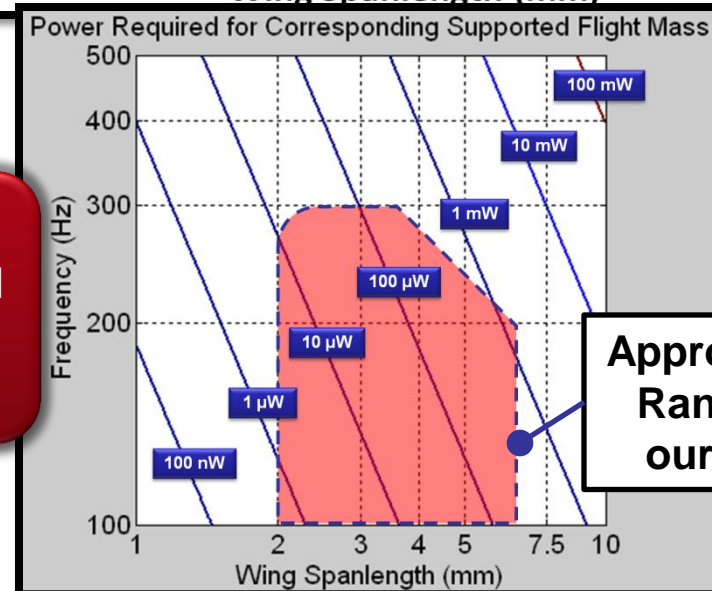X-axis: Length Scale (mm) (0 to 10)

Platform mass to be dominated by mass for power

Key System-level Questions:
– Power
– **Load Bearing**
– Framing the Mobility Design Problem

Power vs Size

Mass vs Size

Mass per leg

Power vs Mass

Flight Mass

Energy

Power vs Limb Properties

Other models

Power vs Wing Properties

Speed, Endurance, etc.

Design

Flight Mass Supported at 120° Φ & 30° α
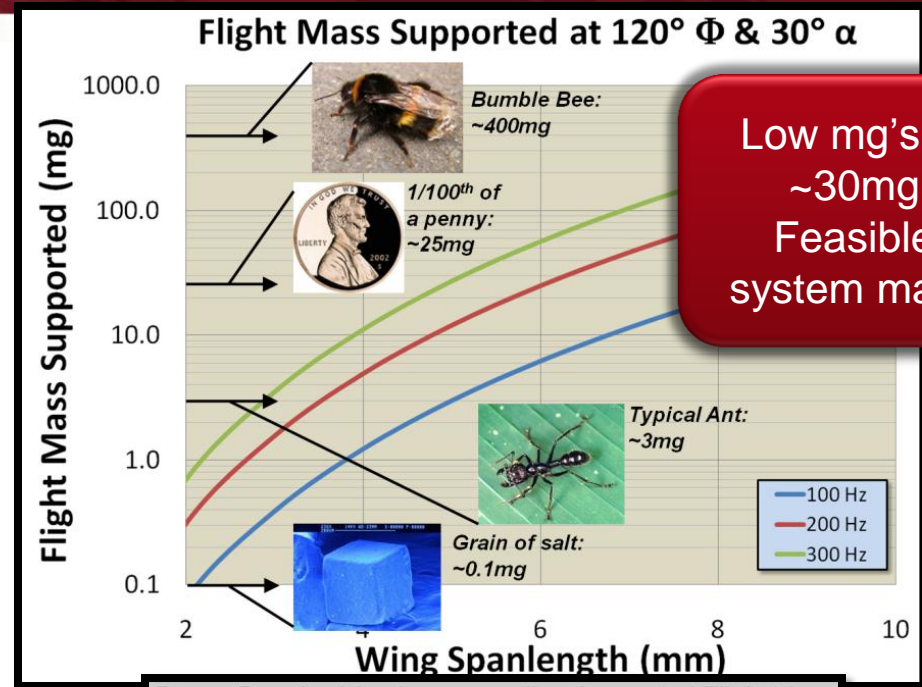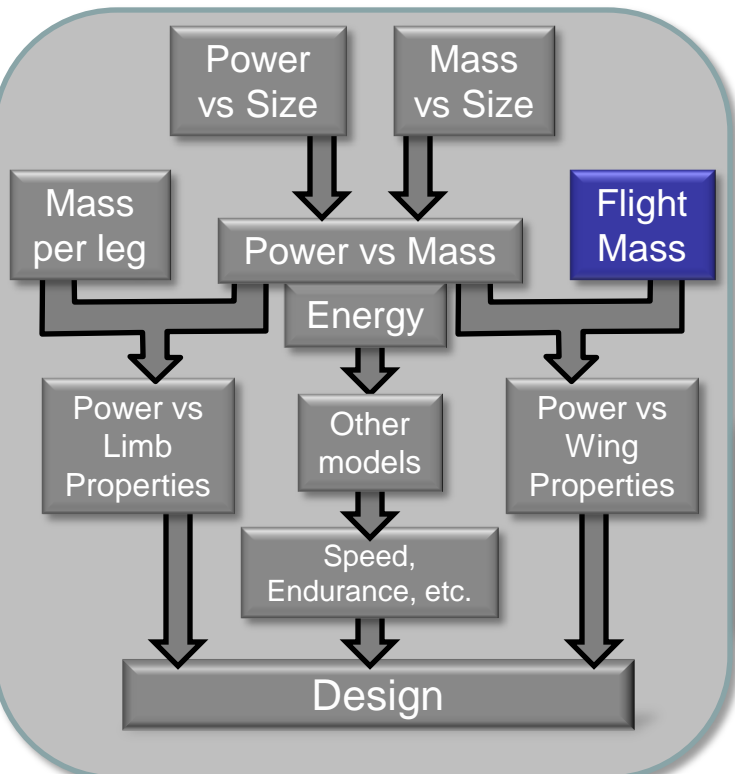
Low mg's to ~30mg Feasible system mass

Bumble Bee: ~400mg

1/100th of a penny: ~25mg

Typical Ant: ~3mg

Grain of salt: ~0.1mg

100 Hz
200 Hz
300 Hz

Power Required for Corresponding Supported Flight Mass
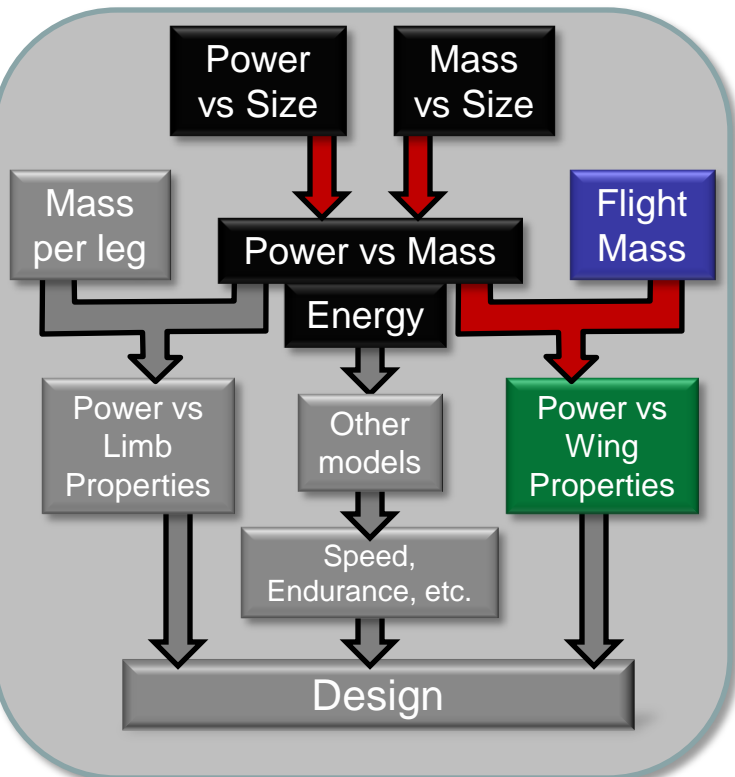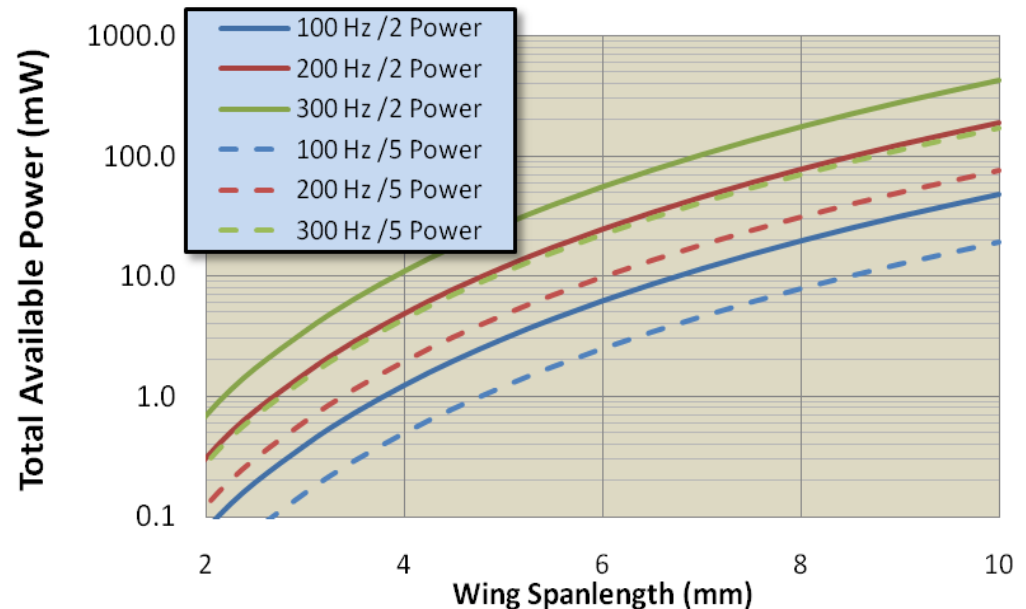

<1mW Mechanical Power Required

Approximate Range for our work

Key System-level Questions:
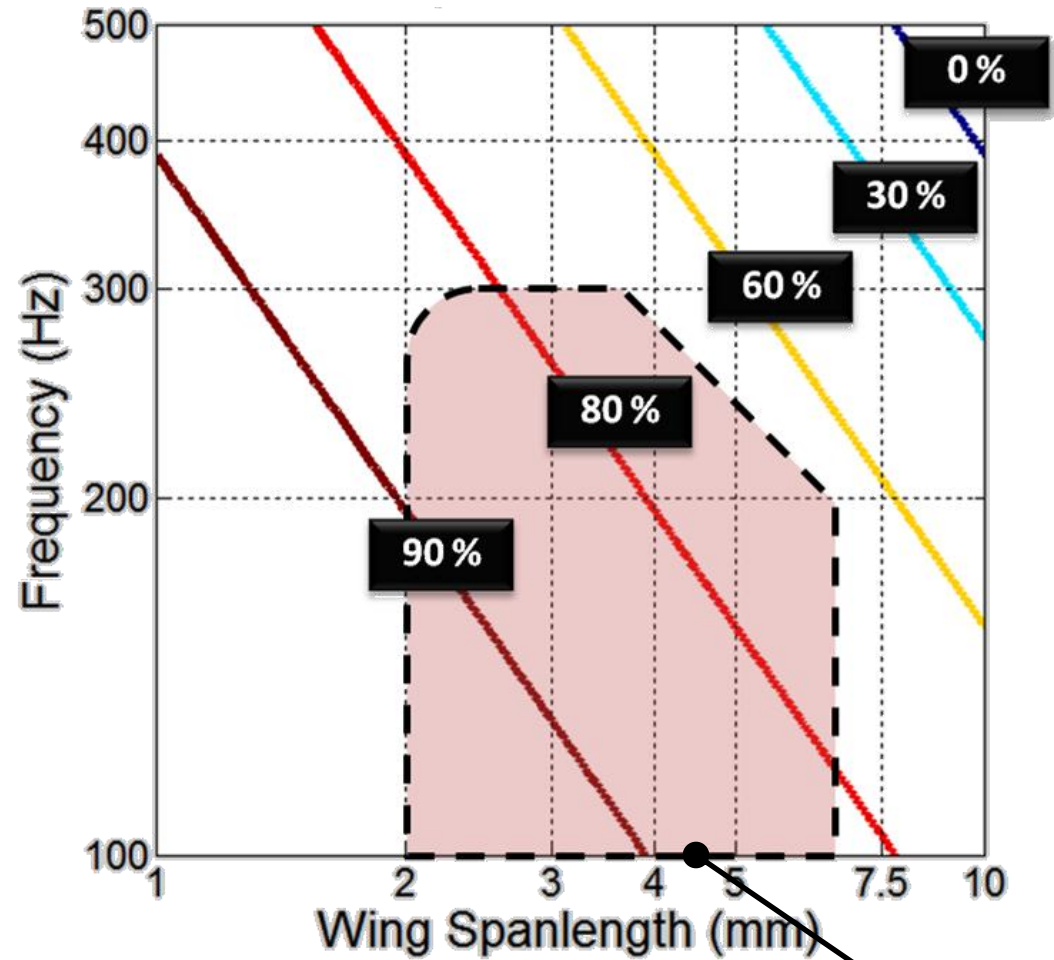
– Power

– Load Bearing

– Framing the Mobility Design Problem
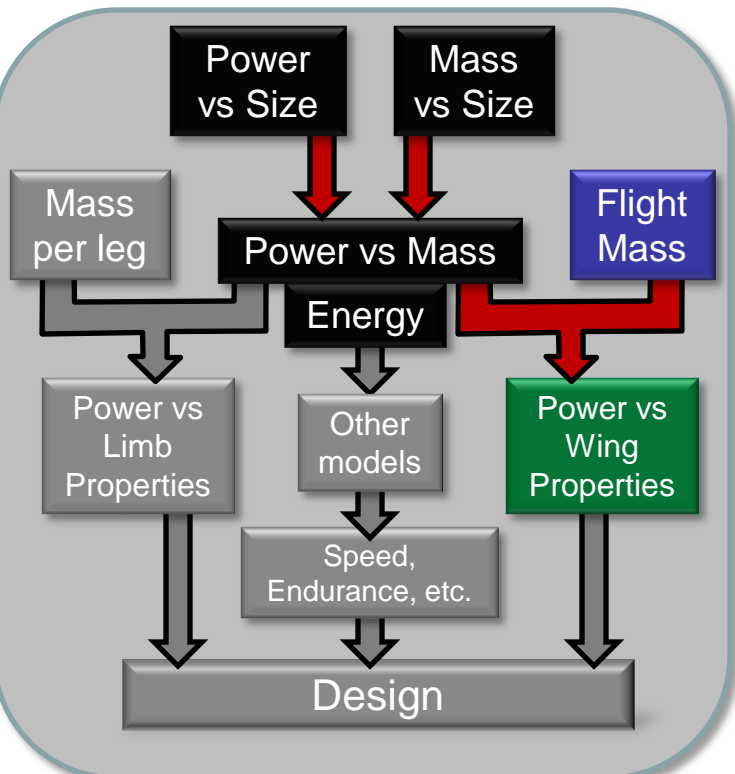

Total Available Power Corresponding to 80% of Supported Flight Mass at 120° Φ & 30° α

Low mW's to ~30mW available battery power can be supported by expected flight forces

Key System-level Questions:

– Power

– Load Bearing

– Framing the Mobility Design Problem

Approximate Range for our work

< 20% of available battery power required to fly

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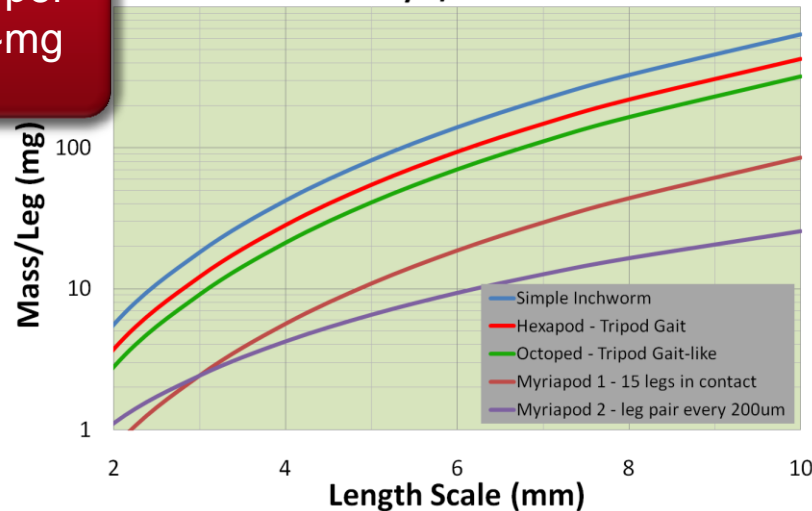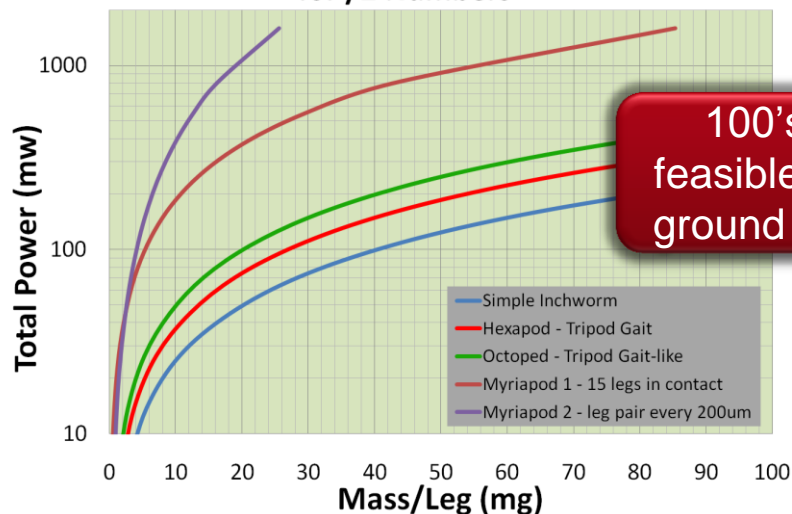## Key System-level Questions:
- Power
- Load Bearing
- Framing the Mobility Design Problem

Mass supported per leg range from ~mg to ~600mg

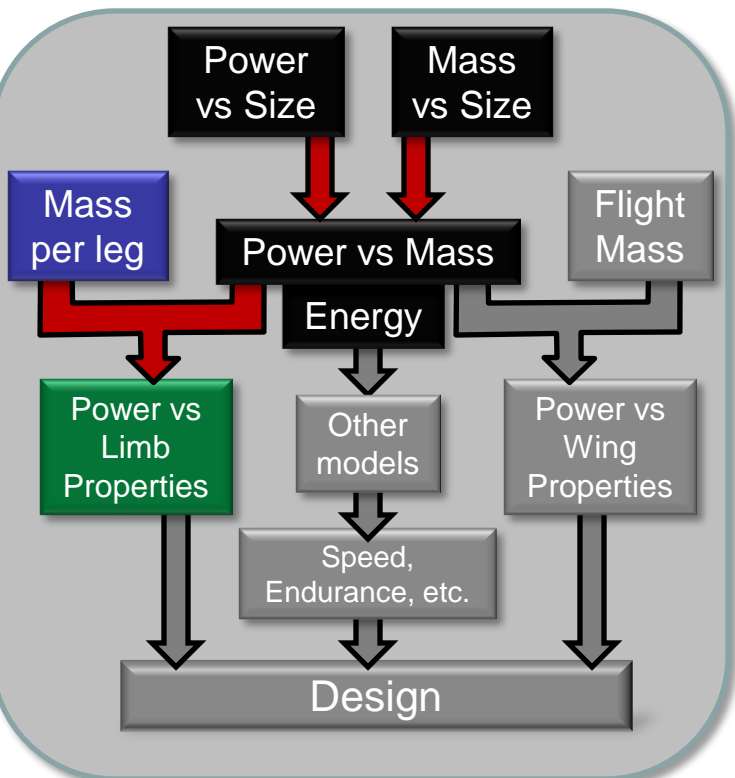**Robot Length Scale vs Mass Supported Per Leg for Battery T/L of 0.5**

- Simple Inchworm
- Hexapod - Tripod Gait
- Octoped - Tripod Gait-like
- Myriapod 1 - 15 legs in contact
- Myriapod 2 - leg pair every 200um

Mass/Leg (mg) vs *Length Scale (mm)*

Diagram boxes:
- Power vs Size
- Mass vs Size
- Mass per leg
- Power vs Mass
- Flight Mass
- Energy
- Power vs Limb Properties
- Other models
- Power vs Wing Properties
- Speed, Endurance, etc.
- Design

Robot Mass Supported Per Leg vs Total Power for /2 Numbers

- Simple Inchworm
- Hexapod - Tripod Gait
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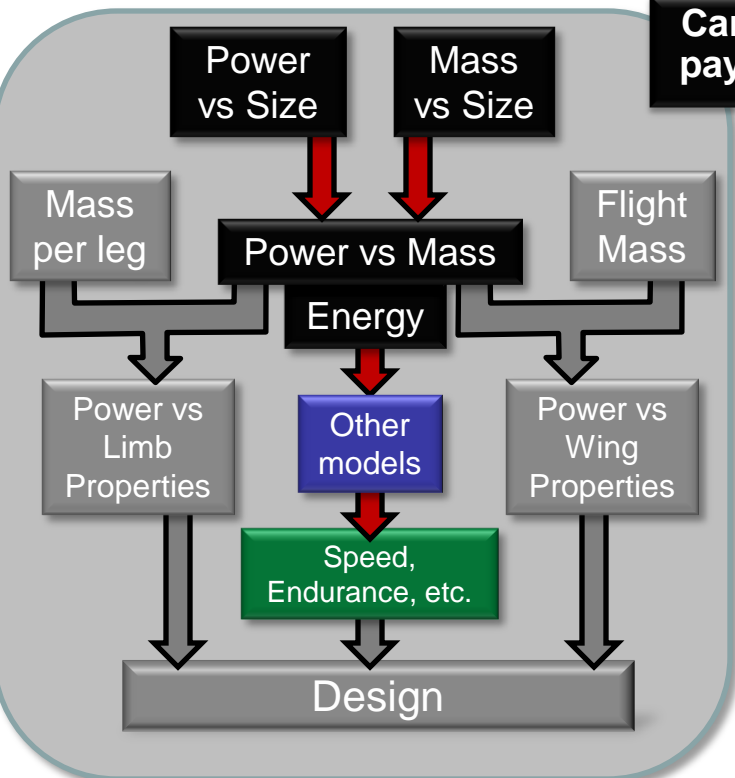
Total Power (mw) vs *Mass/Leg (mg)*

100's mW to >Ws feasible to support with ground mobile systems
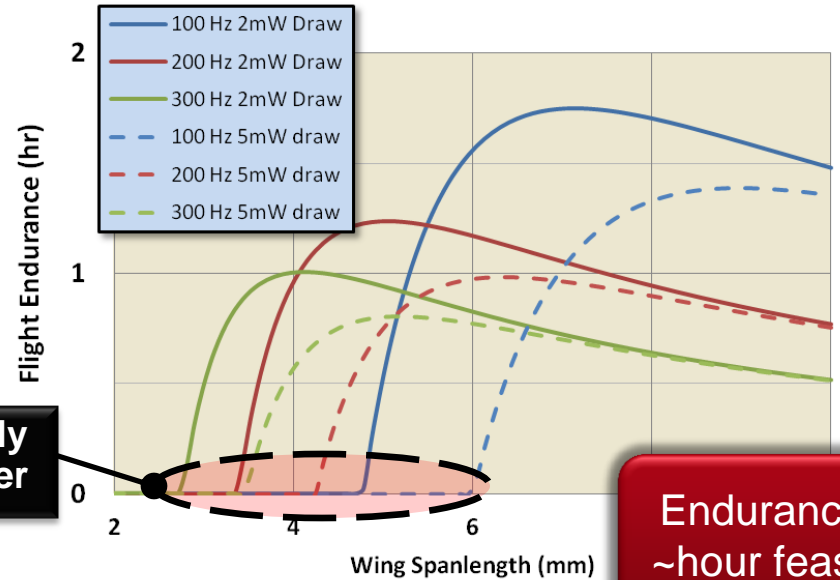
HTER FOCUSED.
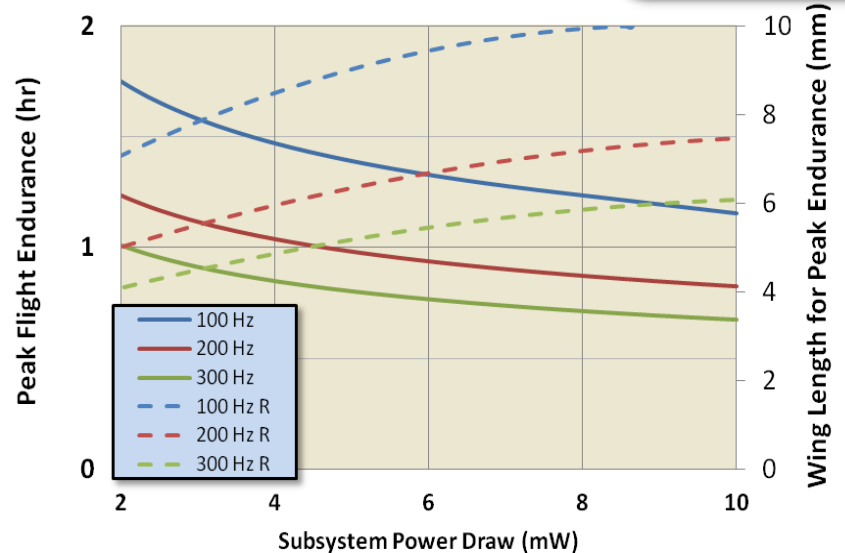
Key System-level Questions:

- Power
- Load Bearing
- Framing the Mobility Design Problem

Cannot supply payload power

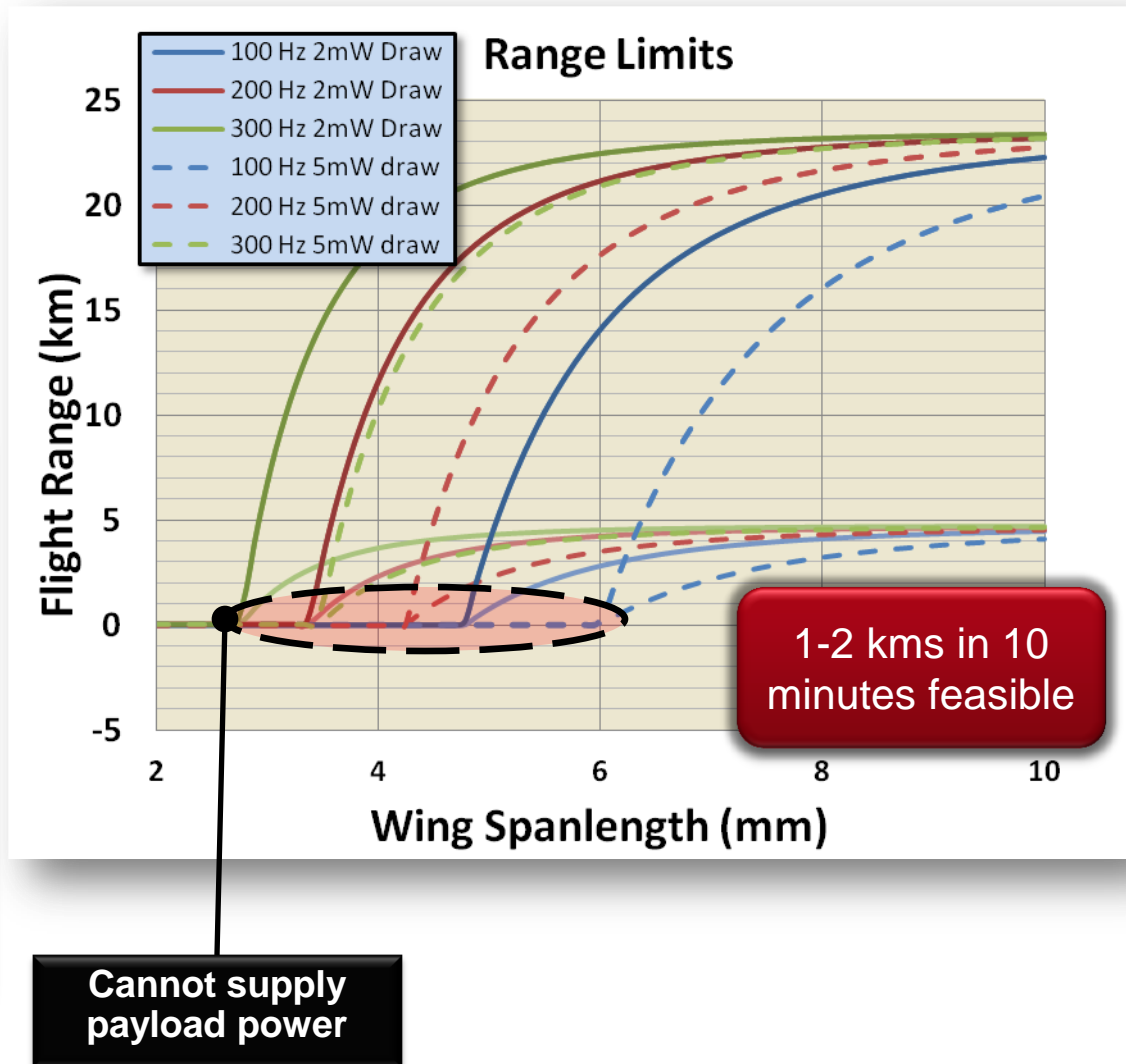**Endurance of ~hour feasible**

Power vs Size → Power vs Mass ← Mass vs Size

Mass per leg

Flight Mass

Energy

Power vs Limb Properties
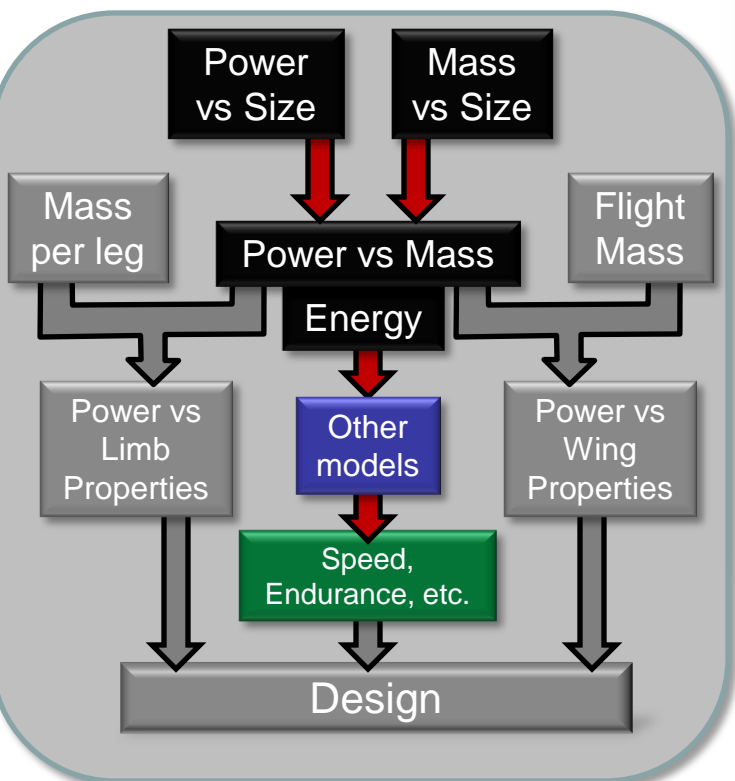
Other models

Power vs Wing Properties

Speed, Endurance, etc.

Design

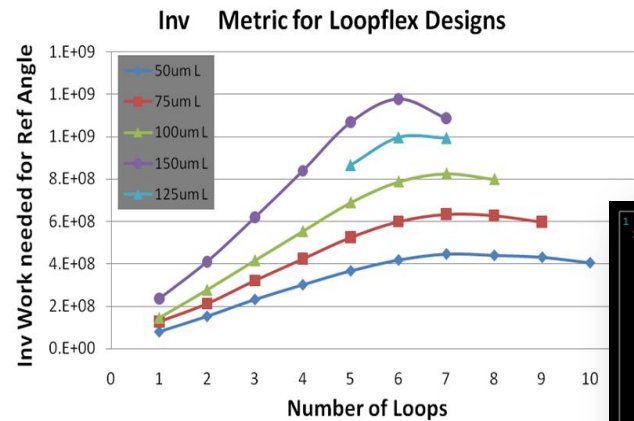## Key System-level Questions:

– Power

– Load Bearing

– Framing the Mobility Design Problem

Range Limits

- 100 Hz 2mW Draw
- 200 Hz 2mW Draw
- 300 Hz 2mW Draw
- 100 Hz 5mW draw
- 200 Hz 5mW draw
- 300 Hz 5mW draw

1-2 kms in 10 minutes feasible

Cannot supply payload power

Enables analytical & numerical model based Design within system context

Inv   Metric for Loopflex Designs

Insect Load Bearing FEA

Power vs Size

Mass vs Size

Mass per leg

Power vs Mass

Energy

Flight Mass

Power vs Limb Properties

Other models

Power vs Wing Properties

Speed, Endurance, etc.

Design

Unimorph Cantilever Loaded Tip Displacement
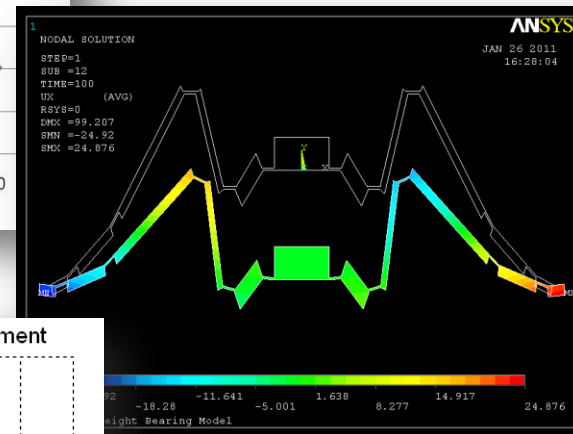
Rotational Actuator Design- FEA

TECHNOLOGY
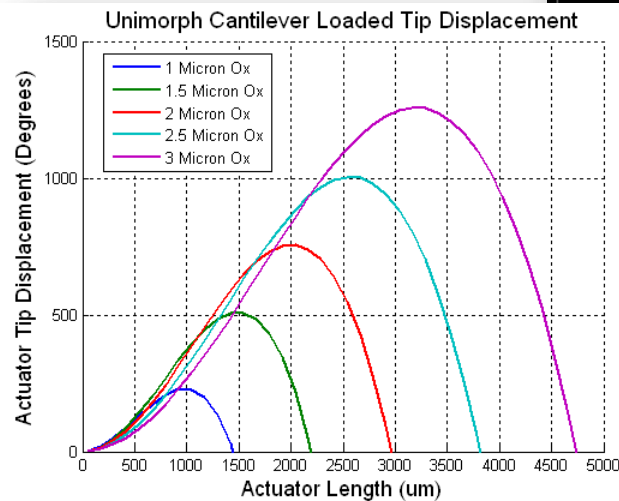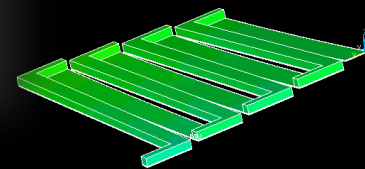
At mm-scale:

- Batteries alone:
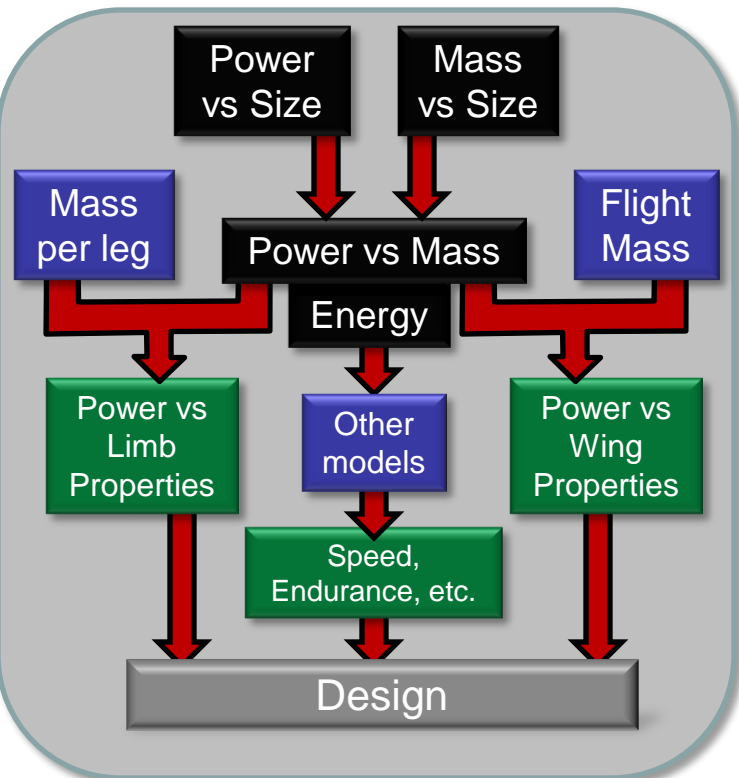 - ~10 to 1000 mW available Power
  - ~10 to 1000 mg Mass
  - Platform dominated by power mass

- Flight:
  - <30mg system mass
  - <30mW available battery power can be supported by flight forces
  - < 20% of available power required to fly
  - Several hours endurance feasible
  - 1-2 kms in 10 minutes feasible

- Ground:
  - Mass/leg range from ~mg to ~600mg
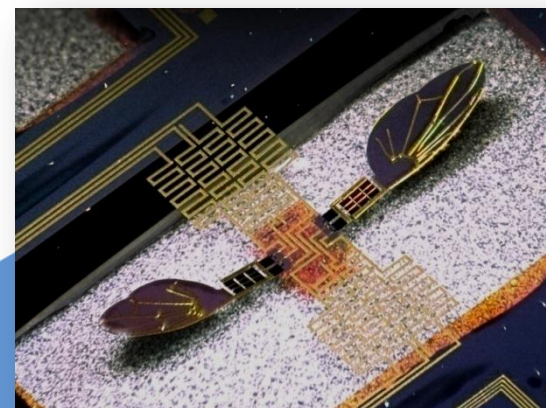 - 100's mW to >Ws feasible to support with ground mobile systems

Diagram boxes:
- Power vs Size
- Mass vs Size
- Mass per leg
- Power vs Mass
- Flight Mass
- Energy
- Power vs Limb Properties
- Other models
- Power vs Wing Properties
- Speed, Endurance, etc.
- Design

Daedelus Systems & UMD

Harvard

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10's g (10's cm-scale)

100's mg (cm-scale)

10's mg (mm-scale)

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